Renewable and Sustainable Energy Reviews 29 (2014) 780–792

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Off-shore wind farm development: Present status and challenges

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ARTICLE INFO

Article history:
Received 26 January 2013
Received in revised form
13 August 2013
Accepted 24 August 2013
Available online 29 September 2013

Keywords:
Offshore wind farm
Converters
VSC-HVDC
Submarine cable

ABSTRACT

Offshore wind farm (OWF) is an emerging technology in the wind energy conversion system. These wind resources are abundant, stronger, and are more consistent in terms of their availability than land-based wind resources. As a matter of fact significantly higher energy production is achieved due to larger wind turbine ratings and stronger wind profiles.

This paper highlights the present scenario and challenges in development of offshore wind power. The challenges and opportunities that exist in the development stages of an offshore wind farm project, from exploration to erection and installation of wind turbines, construction of platforms and laying of sea cables, up to maintenance and de-commissioning, involving important technical aspects are addressed. An application of high voltage direct current (HVDC) transmission for integration of large scale offshore wind farm with onshore grid is attractive as compared to high voltage alternating current (HVAC) transmission system. To make the offshore wind farm feasible, reliable and secure, the different aspects in its planning, design and operation are also reviewed in this paper.

Contents

1. Introduction

Due to depletion of the fossil fuels, leading to acute scarcity of energy production from the conventional source, there is an upsurge in utilization of the non-conventional energy resources like wind,

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http://dx.doi.org/10.1016/j.rser.2013.08.108

solar, biomass etc. Offshore wind farm (OWF) is expected to become a major source of energy globally due to its several advantages. The major utilization of OWF is remarkably visible in European countries and some parts of the United States. The generation planning for next decade i.e., up to 2020 is on a full swing supplemented by numerous statistical data available from different agencies. The challenges in its installation and reliable operation are significant. The shallow water makes a major obstruction as it effects reinforce structure because the water is not remarkably deep, its basement structure may not be solid, which makes a major hindrance for initial installation, etc.

In the past, the negative impacts have developed a great deal of opposition to the first OWF proposals in the U.S. and in turn delayed its development. In [1] the authors have investigated the positive and negative impacts of offshore wind energy. In this context, the cost factor and benefits of offshore wind relative to onshore wind power and the conventional electricity production is discussed.

As of today's status, the wind power generation is considered to have huge potential for its growth. Europe continent is the leader in offshore wind energy having its first OWF installed in Denmark in 1991. In the late 1990s single wind turbine (WT) with power ratings less than hundreds of kilowatts were installed but today, OWFs are planned with capacities even above 1000 MW. Thus, it may be said that OWF have generation capacities comparable to existing conventional power plants.

The bar chart given in Fig. 1 represents the world wide wind energy installation at present and its estimated future growth [2]. From the bar chart it is reflected that there is a remarkable augmentation of OWF installation up to the year 2020. However, this growth in estimated generation is less than onshore wind farm. Hence it can be concluded that the road map of OWF is brighter and in the global scenario, its implementation as a major energy production will definitely become predominant in future. A comparative trend in growth of onshore from year 1992 to 2004 has been compared to estimated growth of OWF in Fig. 2. This suggests an increased potential for growth for OWF in years to follow.

The wind energy conversion in to electric form is carried out using either fixed speed or variable speed generators. In order to achieve maximum extraction of available wind power, variable speed

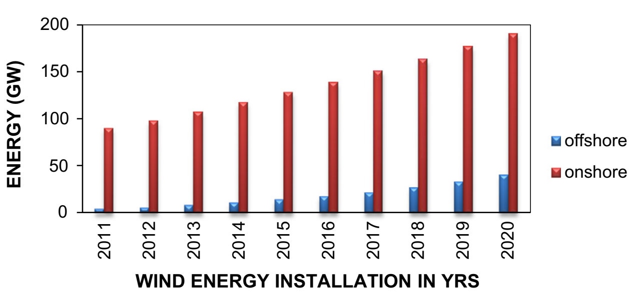
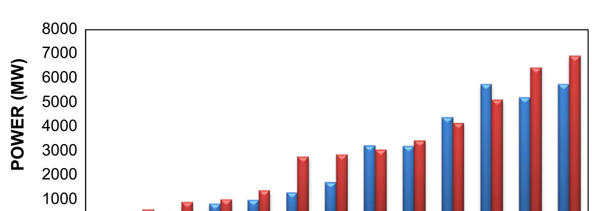


Fig. 1. Wind energy installations: 2011–2020(GW).



	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Onshore(1992-2004)	215	367	470	809	962	1277	1697	3225	3205	4377	5743	5203	5749
Offshore(2008-2020)	374	584	893	1000	1370	2767	2859	3053	3433	4145	5115	6419	6902

Fig. 2. Onshore historical growth 1994–2004 compared to EWEA'S offshore projection 2010–2020 [].
Source: EWEA 2011

operation is preferred over the fixed speed machines. Variable speed machine maintains steady output under varying wind conditions. The various AC machines like, doubly-fed induction generators (DFIGs), wound rotor induction generators, synchronous generators (SGs) or permanent magnet synchronous generators are used with variable speed wind turbines. However, among these, DFIGs are the most widely used due to its overall low cost, its modular, compact and standardized construction. Though, this machine has a complex drive train and requires effective pitch control [3], its advantages outweigh the disadvantages and have become a viable option. These machines are basically wound rotor induction generator having its rotor connected to grid through a back-to-back converter. The converter is one-third of the machine rating. Most of the OWFs use 20 kV or 33 kV voltage level for interconnection of individual wind turbines and then stepped up to 150 kV level to feed power through one or more cables to the grid. Another transformer may be needed for connection into 400 kV grids.

DC system technologies are beneficial for large scale integration of wind energy system which reduces cost and minimum grid impact as the bulk power is concentrated at single point of entry. For increased level of wind farm penetration, grid connection codes have constituted new challenges to wind farm control, design, operation and development. Thus we have to place significantly large structures of transmission and distribution system technology at offshore locations. Large wind farms that are composed of multi-megawatt wind turbines for an aggregate power potential have generally hundreds of turbines or even more. The interconnection of these units represents a technical challenge due to its location and stochastic nature of power produced. All OWFs operational today, are radially connected to the onshore electric grid through use of high voltage alternating current or high voltage direct current submarine cables. As HVAC subsea transmission schemes has limitation to the transmission distance, high power losses and resonance problems, HVDC transmission schemes are preferred. Due to the predominant capacitance effect of these AC cables, a large distance and amount of transmitted power is technically not feasible. The most economic solution for the connection of relatively large OWFs (500 MW and above) at a distance greater than 50 km, lies with the use of a HVDC link. This is advantageous against the undesirable effects of capacitance in submarine cables, and the corresponding high reactive currents, with the use of HVAC transmission lines.

The power through HVDC link is possible to vary the voltage of the offshore AC network in order to (i) avoid use of transformer tap changers, (ii) avoid use of a static compensator (STATCOM) or synchronous compensator and (iii) use an uncontrolled rectifier instead of a controlled one. It is also economically advantageous as diodes are cheaper, do not require gate drivers and have low losses. In addition, absence of STATCOM and transformer-tap changer increases the system reliability. Currently, two converter technologies are commonly used for marine HVDC links, namely voltage source converters (VSCs) or line commutated converters (LCCs). VSCs are based on IGBTs, GTOs or IGCTs, whereas LCCs are based on thyristors. LCCs were developed about 50 years back and LCC-HVDC shows remarkable advantages in terms of power rating and losses. The LCC based HVDC integrated with a large offshore DFIGs-based wind farms connected to the main onshore network is controlled by STATCOM [4].

Due to an increased penetration level of wind farm, its impact on operation of power system components exaggerates. Consequently, this has lead to active research works on various issues; planning and design, security, protection, stability, reliability and power quality.

A review of the important modeling techniques employed for developing flexible AC transmission system (FACTS) controllers is given in [5]. The authors also examine the role of HVDC-light transmission in exploiting the offshore wind energy resources.

There are different arrangements for wind farm collector systems and the grid can be designed for AC, DC or both AC and DC. Shao et al. [6] discusses the layouts in terms of losses and economics. The radial layout provide low cable cost and simple control algorithms, while ringed layout are preferred in terms of reliability and power losses during normal operation. Single return layout enables alternative routes for exporting power during unpredictable faults and on other hand, star layout is used to reduce cable rating and provide high level security. The network with multi hub ring layout is used to achieve low losses through high voltage collection of power.

Multilayer sea marine power cables are also important components of HVDC power transmission system. Polyethylene (PE) HVDC cables offers significant advantages like high conducting temperature, light moisture barriers and simple joint method. Polymeric insulated HVDC cables has disadvantage as cable breakdowns upon polarity reversal. To address the major issues in DC cables, advanced semiconductor devices like IGBTs used in VSC based HVDC transmission is viable option [6]. Another important factor in DC power transmission is DC circuit breaker. For medium voltage application, a mechanical system with a properly designed snubber circuit should be used, and for high voltage application, a solid-state circuit breaker is preferred.

Although in recent past, numbers of research publications/projects are published/implemented, still there are many technical challenges left which draws our attention. Thus, this comprehensive review in the development of OWF is an attempt to address key issues in its reliable growth in energy sector. Some of these challenges include specific intermediate equipments, its integration topology, protection, operation and maintenance, and last but not the least, environment and ecological aspects.

Recently, some reviews are published in the area of offshore wind farm. The survey [6] describes about the configuration of layout/components, without much stress on associated problems or works reported by different researchers, while Ref. [7] is dedicated to welfare economic costs with respect to location of wind farms.

This review also brings in an attempt to discuss the important issues; electrical, civil, mechanical, management, policy, even ecological aspects related to development of offshore wind farm. The present trend that exists in technologies and future scope or challenges is addressed for its successful growth in energy sector.

2. Offshore wind farm development

2.1. OWF installation

The tower structures including wind turbine-generator set in OWF are installed in seabed. And due to technical reasons, it becomes difficult to anchor the tower structure directly on the seabed in deep water, where higher potential for generation exists.

In the past, the development of OWF with fixed support platforms were based on the experiences gained from onshore wind turbines installation. However, in such fixed platform types, the high frequency excitations due to rotating blades and tower flexibility causes resonance to occur at its natural frequencies. As a result, may significantly shorten its fatigue life when the water depth increases [8]. Recently, in year 2009, the first floating offshore wind turbine was installed by Statoil-Hydro and Siemens on the coast of Karmøy, near the port of Bergen, Norway. The floating supported structures have greater flexibility of construction and installation procedures. Also, they can be easily removed from the OWF system. In general, floating OWFs are considered more complex in design and installation. In floating type supported structures, most important issues are wind turbine thrust and loads due to occurrence of sea waves, especially dynamic component due to individual waves. The up wind yaw stability is also an important one that must be taken into consideration for the control of floating WTs. There are number of prototypes that are in the planning stage for floating type offshore wind turbines, like Blue TLP. This is off-grid demonstration prototype which is installed in Italy and Arcadis TLP in Germany [9]. In future, floating type structures having capability to be controlled against aerodynamic loads, and hydro dynamic loads are expected to get developed.

2.2. Grid interconnection and power evacuation

Traditionally in the past, wind energy generation has remained connected to the electric grid assuming that its size and influence are small. This has lead to connection requirements being less stringent. Typically, wind farms do not contribute towards stabilization or regulation of AC grid and in many cases detailed transient or stability studies are not performed. However in recent years, due to large penetration of wind power in the order of hundreds of MW, their impact have been significantly observed on the host grid and thus interaction issues need to be carefully investigated. Thus, new integration solutions are sought, taking into consideration the properties of AC system including, stabilization, regulation, fault-ride-through (FRT) capability, etc. Meanwhile, the options for cost effective wind farm topologies, their dynamics, transients and efficiency is also examined. Wind farms are now required to comply with stringent connection requirements including; reactive power support, transient recovery, system stability and voltage/frequency regulation, power quality, whereas, scheduling and reserve availability are also considered. The conventional wind generation concepts based on DFIGs may pose difficulties in meeting all the above interconnection requirements [10].

OWFs are different from onshore wind farm on grid interconnection point of view. It has been recognized that many of the above network-connection issues would get eliminated, and even AC system stability might enhance, if the wind power connection point incorporates a converter system. The interconnection with AC network (onshore grid) on other hand would require use of SVC/STATCOM for reactive power and voltage support. Fig. 3 shows the block diagram of offshore wind farm interconnection

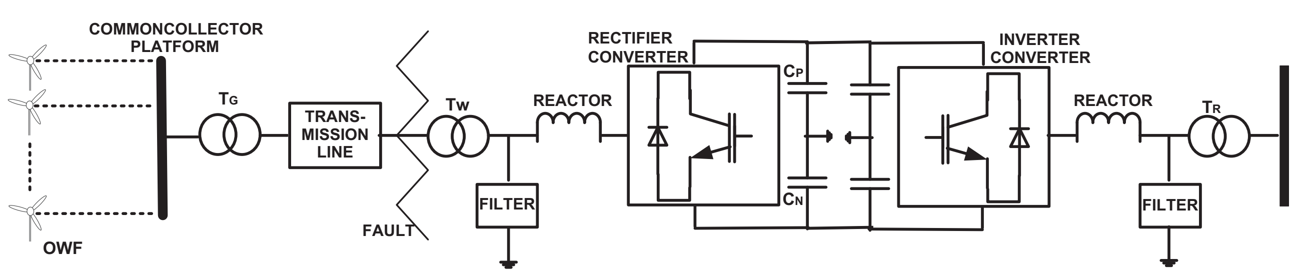


Fig. 3. Block diagram of offshore wind farm interconnection to onshore grid.

to onshore grid through VSC-HVDC converter topology. But still, these do not resolve the issues related to low inertia, power and frequency control/stabilization of AC system, which rather becomes significantly important with large wind farm interconnection.

The OWF interconnection to onshore grid through HVDC link is different from the traditional HVDCs links. The main differences lies in the unidirectional power flow and the possibility of taking advantage of the flexible control characteristics of the wind turbines. Traditionally, HVDC link provides AC frequency stabilization [11] or AC voltage regulation. VSCs in HVDC system are more versatile and provide faster controls [12,13], which may be utilized at the wind farm interconnection point. A VSC converter enables independent voltage, frequency and power control. A wind farm interconnected with HVDC link therefore has the potential to offer grid control functions similar to a conventional generator. The authors in [14] present a converter configuration concept with an aim to reduce its cost in implementation of HVDC line, through utilization of variable speed operation. The inverter regulates the DC voltage, common to all converter station. Each rectifier regulates the DC current in its own branch. If VSCs are employed it is possible to regulate the generator speed, voltage and operate each VSC at different frequency with optimum speed regulation for each turbine group.

In past, there does not arise any specific requirement for wind farm grid interconnection codes, which are discussed in detail in later section of the manuscript. Recently, some of the European countries like, Denmark, Germany and Spain [15–17] have issued grid interconnection codes addressed to wind farm, both at transmission and distribution level. A number of OWF configurations for collection of power and to feed into the grid have been suggested. Thus, electricity produced goes through many conversion stages, both via AC transformers and via AC/DC and DC/AC converters. A configuration that minimizes the number of conversion stages would be advantageous both from an initial cost and system efficiency perspective. This has led to significant research work in the area of DC collector grids [18–20]. The authors in [20] present a single active bridge converter (step-up) to reduce losses. It is concluded that one main (common) step-up converter provides best solution for long distance transmission, however, this in turn requires installation of a platform in the sea. Another approach in [21,22] implements series connection of wind turbines through current-source inverters (CSIs). Each converter carries the same current, with DC link voltage being sum of the converter voltages. This configuration regroups the wind turbines into small clusters, each consisting of four units to counter the cost of CSIs. A multi-terminal DC grid is formed. However, this configuration cannot have independent operation of each wind turbine, being grouped in clusters. Also, the failure of one converter will force all the four units to shut down.

Any economical configuration chosen for interconnection should not include construction of platform, also have reduced number of expensive power electronics components and number of transformers. Veilleux et al. [23] propose a series interconnection of distributed converter modules between the wind turbines. This forms DC voltage for transmission purpose. The step-down buck converter provides a continuous conduction path for the DC link current. The proposed topology eliminates all transformers at the sending end, and requires no offshore platform for the rectifier station. This significantly reduces cost. Some researchers [24,25] have reported substantial advantages obtained from integration of OWF with wave energy converters into a single offshore marine renewable energy farm. This combination leads to reduced hours of zero power output [26] and also reduced inter-hour variability. The combined farm allows a reduced capacity of offshore transmission system. A tool for calculation of statistical specifications of wind sites and that aids in information on design of combined wind and wave farm is given in [27]. The study on sharing of electrical infrastructure between these two energy resources is explored in [28,29]. As reported, the generation profile in combined farm is entirely different from operation of either of the farms. An optimal configuration is suggested in [30] and rating of the transmission link depends on the generation mix of combined wind and wave energy farm. With the availability of VSC-HVDC configuration, an optimized transmission line capacity is determined for a given mix of wind and wave energy for various offshore distances. This investigation is carried out for 1000 MW farms at three locations of the California coast at distances from 30 to 60 km in [31]. The difference in power output profiles of a 100% wind farm, a 100% wave farm and their combination results into selection of reduced transmission capacity. The methodology considered the optimal selection from the developer's perspective.

2.3. Converters

As in the OWF, transmission of power is accomplished through a long distance, DC transmission in this context is feasible. Thus the HVDC converter plays a major role for transmission of power from offshore to onshore grid. Earlier the HVDC transmission technology being used was mainly realized by using current source converters (CSCs) commutated thyristor switches, known as traditional HVDC or classic HVDC. However, the advantages of VSC-HVDC are exploited for grid integration objective of OWF with respect to power rating and loss reduction since, the first 50 MW offshore VSC installation in the year 1997. VSC was taken offshore on oil and gas platforms from shore in the year 2005. Now OWF connections up to 900 MW with losses less than 1% per converter are in construction stage. The VSCs use insulated gate bipolar transistors (IGBTs) valves and pulse width modulation (PWM) to produce desired voltage waveform. The VSC-HVDC transmission system consists of two VSCs, transformers, phase reactors, AC filters, DC-link capacitors and DC cables. The two VSCs as shown in Fig. 3 may be seen as the core of this transmission system topology. One of the VSCs works as rectifier, while the other one works as an inverter, and both of them are based on IGBT power semiconductors. The two VSCs are connected through a DC transmission cable. Mainly, two basic configurations of VSCs are used on HVDC transmission system. The use of thyristors in line commutated converters (LCCs) has some serious drawbacks in terms of high short-circuit capacity, reactive power consumption, commutation failure caused due to AC under-voltage, etc. The VSC-HVDC topology offers significant advantages from its control point of view and has constantly increased power levels in the past years. However, LCC-HVDC still shows clear advantages, especially at powers from 400 MW and above [33]. The power handling capacity of a single IGBT power device used in VSC HVDC is lower than corresponding capability of a thyristor used in LCC-HVDC. Currently, although the VSC-HVDC technology seems promising and manufacturers offer systems with a transfer capacity of 1100 MW at a DC transmission voltage of ± 300 kV [34], LCC-HVDC still shows major advantages in terms of power rating and power losses [32].

Since the voltage regulation of offshore grid not being critical and power flow through HVDC remains unidirectional, it is possible to substitute the thyristor based HVDC rectifier by a diode based uncontrolled rectifier [35]. This economizes the cost of power electronic devices, low conduction and commutation losses and eliminates the need for gate drivers. As a result, in turn enhances the converter operation efficiency. These reduced losses compensate the additional losses due to use of full rated converters within WTs. Moreover, additional cost reductions are achieved by the elimination of STATCOM and rectifier transformer tap changer, with increase in

overall system reliability. A technically feasible study on black start with use of diode based HVDC is given in [36]. The authors indicate that for adequate start-up, at least some wind turbines can be provided with local energy storage for ancillary services like basic control equipment, brake, yaw and pitch actuation. However, in the study it is shown that, a large reactive power is drawn during the starting transients. The authors in [37,38] present a detailed study on the self-start operation of OWF connected using rectifier scheme, considering the influence of the WT DC-link and mechanical dynamics. A distributed control algorithm for joint control of WT and HVDC diode rectifier that leads to performances similar to those obtained with thyristor controlled rectifiers is also demonstrated. The combination of WTs and HVDC diode rectifier can be operated either in voltage or in current control mode.

The use of aggregated models of 32WTs, each of 5 MW for VSC-HVDC coordinated control to improve the dynamic stability is discussed in [39]. The study is focused on overall dynamic response of entire wind farm instead of each WT. Those WTs with similar dynamic response are grouped into coherent group and then aggregated as an equivalent machine. The generators with similar rotor-angle swing responses limited to 5–10° during large disturbances are selected into the same coherent group. The authors have assumed constant wind speed for all WTs operating at maximum power point; WT-DFIGs in the same row and other equipments have identical parameters and disturbances occur outside the wind farm.

3. Offshore wind power control and operation

3.1. Voltage and frequency control

Several techniques have been proposed for voltage and frequency control. The system without using STATCOM is controlled by classical voltage and frequency droop characteristic in order to achieve well shared active and reactive power. DFIG is connected to the grid via HVDC has capability to supply constant voltage and frequency at stator terminals irrespective of the shaft speed [40]. Some techniques also use STATCOM [41] for the control objective. The techniques rely on rectifier firing angle to control directly or indirectly the offshore grid voltage and frequency. These techniques however, cannot be applied in diode based HVDC rectifiers. The control approach [37] uses reactive power to control voltage and active power to control frequency during both islanded and grid connected operation. It is shown that during islanded operation, adequate voltage and frequency is achieved even when contribution from some WTs is not met. The combined operation of WTs and HVDC diode rectifier can be either in current or voltage control mode. Also the tap-changer of the HVDC rectifier is no longer required.

3.2. HVDC power control

Power control in the context of HVDC transmission is necessary to enhance the reliability of an integrated system. Further to enhance the power transmission capability, the multiterminal wind farm is commonly used with integration of HVDC cable which reduces the cost of new wind farm. The offshore grid AC voltage and HVDC inverter controllers are designed to perform coordinated control action of HVDC link transmitted power. The coordinated control action provides an adequate regulation of both HVDC voltage and current. HVDC power flow control can be achieved by either [43]:

- HVDC current control by modifying the offshore grid voltage, while the HVDC link voltage being controlled by the onshore inverter. This approach has reduced filter size and reactive power consumption on the onshore grid, but the WTs have to provide a fast offshore AC grid voltage control to limit HVDC over current. Also, with constant γ control, a large range of offshore voltage variation is required, which is only achieved by WTs with full rated converters, i.e. those coupled to SGs.
- HVDC current control by the onshore inverter, with HVDC voltage being controlled by modifying the offshore grid voltage. This method allows a small variation of offshore grid voltage during transients, at the cost of huge reactive power consumption, especially during transients. This control method is used in DFIG based WTs having onshore voltage source inverters.

The above two control strategies have been in practice; however a combination of these can have advantage of their respective characteristics. In case of sufficiently low offshore AC grid voltage, the inverter will control the HVDC link current. At the same time, the inverter will function for minimum γ control action to ensure safe operation. Direct power control (DPC) is used to control active power output of wind farms. This control algorithm for voltage stability, active and reactive power control is discussed in [44]. The DPC method is simple and it can even control the power output of wind farm by the predetermined curve of wind power output. A double loop control is applied in inverters. This loop control strategy has fast dynamic response and high accuracy. This mitigates voltage fluctuation, harmonic and flicker caused by offshore large scale wind farm. In the study [45], the authors present three control strategies; (i) inverter voltage control, HVDC link current controlled by the offshore voltage, and power controlled by varying the offshore voltage, (ii) inverter current control, and power controlled by offshore voltage variation, and (iii) inverter current control, and power controlled by variation of HVDC link current reference. An aggregated model of wind farm is considered, though the offshore AC grid voltage control strategy should take into account the model of individual wind turbines [40].

AC power cables have many limitations owing due to the increased capacity of HVDC transmission system. The work in [42] presents an alternative to the conventional HVDC for connection to wind farms. By connecting WTs with synchronous generator and full power converter directly to HVDC line gives many advantages such as failure in the converter at generation site does not affect entire wind farms, low cost of power converters, VSC converters connected to wind farm is not needed. WTs may be tapped to nearby HVDC lines, no need for control circuits in high voltage side as diodes are the only power semiconductors in HV side, etc. Still some issues are yet to be solved like behavior of system when there is fault in AC onshore grid. Secondly DC current interruption is difficult task and DC breakers at medium voltage and high voltage levels are scarce. As the distance increases above 50 kms, use of HVDC link becomes viable economic solution for transmission in OWF, as the link could be based on VSCs or LCCs. The LCCs require external source of voltage and reactive power for operation. So SG or DFIG based WT together with the LCC is used in distant OWF. SG is the best option because it can operate at power factor down to 0.8 and tolerate much higher voltage disturbances in comparison to DFIGs. Also gearless WT is more beneficial and has low maintenance cost in comparison to geared WT. The authors in [32] have presented modeling issues of SG based and DFIG based OWF and have also developed a control algorithm without the use of STATCOM. The HVDC link current control strategy includes a standard control loop with voltage dependent current limit (VDCL) to optimize wind energy abstraction from the turbine's rotational speed and power characteristics.

3.3. Protection and security

Due to economic reasons, simple and non-integrated protection methodologies have been adopted in the design of wind farm.

Bauschke et al. [46] reports different level of damages caused due to limitations of such design. According to new grid codes, wind farms are required to remain connected to grid even during faulty conditions for a certain period and continue to feed active and reactive power.

Wind farm protection system is usually divided into different protection zones including the wind farm area, wind farm collection, wind farm interconnection system and the utility area. In brief, the generator controller provides a typical protection strategy. The generator is protected via its circuit breaker having a breaking capacity of 2–3 times of generator rated current. Electric fuses protect the local step up transformer against short circuits. The collector feeder is protected as a radial distribution feeder by use of over-current relays. The main collector bus, grid power transformer and integrated transmission system are protected through multi-functional relays. The submarine cables are protected through either current differential or distance relays with overcurrent relays as backup protection.

The voltage sag experienced due to faulty conditions in turn significantly reduces the delivered active power to the grid. Thus, excess mechanical power leads to increase in rotor speed. Now, the control scheme acts to prevent over speed and protect power converter [47,48]. Subsequently, failure in coordination or mal-operation of relay may be experienced due to the changes in fault current profile. In addition, submarine cables may cause mal-operation due to the different impedance characteristics and configuration of cable segments. These scenarios should be considered appropriately in design for selecting and setting of their protective devices. One of the protection schemes against above circumstances may have use of triggered crowbar circuit. Though rotor protection is said to be achieved by the trigger of crowbar with deep voltage sag occurrence, however, in turn it leads to loss of generator controllability through machine side converter. This is because, rotor gets shorted through crowbar resistors and machine side converter gets blocked. Another protection scheme uses DC chopper to maintain DC voltage within acceptable limits by short-circuit of DC circuit through chopper resistors. Consequently, action performed by crowbar circuit gets reduced.

A series resistor can share the rotor circuit voltage and hence limit the rotor current during the fault, and hence is an alternative to crowbar protection disturbances because the stator windings are connected to the grid through a transformer and switchgear with only the rotor-side buffered from the grid via a partially rated converter [49].

The authors in [50] report that blocking of rotor IGBTs converter during severe voltage sag leads to non-detection of faults by either distance or overcurrent relays, i.e. its response is significantly affected. The aforementioned problem is solved by use of pilot distance or differential current relays. However, reliable operation of these relays is determined by communication signals between the two. In addition, cable capacitance and shunt reactors located in their respective protective zones may affect the scheme. The authors suggest an appropriate selectivity and time delays to be considered for versatile protection scheme. The study investigates the impacts of the DFIG behavior on the used protective elements against grid faults. For this target, a detailed dynamic modeling of 60 MW offshore is developed in MATLAB. The farm, consisting of twelve numbers, each 5 MW DFIGs, is integrated at voltage of 110 kV via a 70 km submarine cable. Details of the back-to-back converter, rotor protection circuitry and dedicated converter protective system are suitably described in the model.

The work [51] focuses on the maintenance of OWFs. It consists of two medium voltage 33-kV grids connected to three winding transformer and a 150-kV transmission link, transmitting the wind power to the 150/400 kV through a step up transformer. The current and voltage stress of the grid due to a single phase to ground fault is analyzed by considering the types of transformer connection and methods of neutral earthing (solid earthing, isolated neutral, and compensation coil). To show the time response of grid voltages and currents for a single line to ground fault, a realistic wind farm configuration is used while faults at critical points are simulated.

The study on options for neutral earthing at 33 kV and 150 kV voltage levels is investigated in [52]. The authors have simulated a single line to ground fault in a realistic wind farm. The earth fault factor within 33-kV network is limited to 1.4 p.u. by use of solidly grounding method. While, a single line to ground shortcircuit current reaches a value of about 3.4 kA. Though such high current is in acceptable limits of cables, but requires a fast and selective fault clearance by the protection system. The use of grounding transformer in neutral at 33 kV, results into satisfactory current and voltage stress. However, there exists a risk of losing it and thus converting into solidly grounded at the time of fault occurrence. The simulations for 150 kV transmission link shows that solid grounding in the transformer is needed at both ends. The earth fault factor is limited to 1.1 p.u. and fault current limited to 5 kA. These values are considered to be optimal since shield provided in the cable is usually designed to withstand 10 kA short circuit current for duration of 1 s. Still, the main challenge remains to maintain earth fault factor within limits.

In another work [53], a supervised shutdown algorithm to meet required ramp-down rate according to grid code during storm-driven situation is investigated. Shutdown of a large wind farm requires the power grid to have a ramp-up capability large enough to balance between generation and consumption of electrical energy. If the wind speed exceeds the cut-out speed, the number of WTs to be shutdown simultaneously is decided to meet the required ramp-down rate of a grid-code. The shut-down start/end times of each group are decided to avoid superposition between adjacent two groups. The performance of proposed shutdown algorithm is verified under various storm scenarios.

In past, wind turbines were isolated from the grid following its faults occurrence. However, separation of wind turbines with voltage level below 80% of nominal value would lead to undesirable revenue loss. Therefore, utilities prefer to have fault ride through (FRT) capability. WTs must remain connected even when the voltage at the point of common coupling (PCC) with grid reduces to zero. The grid operators want wind farm to participate in grid voltage support in steady state and during fault conditions too. The latter requirement suggests that they should have FRT capability and supply reactive current to the grid as according to the German E.ON grid code. The authors in [54] describe two new control approaches for DFIG-based wind farms connected through VSC-HVDC link with extended FRT capability. In the first approach, full communication between HVDC and wind farm is established. On fault detection at receiving end converter (at end of HVDC line), the active power of WT is reduced by changing the active current set point on machine side converter. This set point is calculated excluding the transmission losses. The control action modifies the power balance between sending and receiving end and limits the HVDC voltage to 135% of its nominal value. This short-time over-shoot, though acceptable in HVDC cables, but needs to be considered in converter design. While in second method, communication between two HVDC terminals is established. When a fault occurs, voltage drop is initiated and active power gets reduced at a faster rate comparatively. As a result, HVDC voltage rises up to 120%. This approach prevents the typical DFIG short circuit currents having DC components, and reduces the mechanical stress on the generator and the drive train. The proposed control method for VSC-HVDC converters is capable to achieve variable speed operation of permanent magnet SG driven WTs [55].

An uncontrolled offshore rectifier offer economic advantages, however, fails to provide active protection against over-currents

caused due to onshore grid, inverter or HVDC link faults. However, an integral design of WT and HVDC controller is demonstrated to perform competitively with conventional thyristor based HVDC links in [35].

The simulation results [56] demonstrate the grid support capability of the VSC-HVDC through contribution of reactive power and thereby re-establish the grid's voltage during the grid fault. The investigation is demonstrated on a 165 MW offshore wind farm with induction generators for low voltage fault ride through (LVFRT) capability with SVC units at the point of connection with the grid. The SVC injects reactive power to the grid during fault to counter the drop in AC terminal voltage, and it decreases as voltage recovers from the fault. A power-reduction control strategy is applied at WT control, offshore and onshore converter control in [57]. This improves the transient performance of the OWF during grid disturbances. The use of local measurements according to generalized dynamic voltage collapse index gives preventive measures like security, stability and reliability. In [58], two generalized voltage collapse indices, which represent the distance to voltage collapse in terms of loading margin to maximum loading, suitable for OWFs connected through long transmission system are derived and analyzed.

The authors in [59] have modeled 184 MW OWF located at 45 km from the PCC. The study is shown for FRT capability for two types of interconnections; VSC based HVDC and AC cable. The wind turbine-generator set in AC cable interconnection experiences the largest speed deviation from the nominal value. Also quick recovery in active power transmission to onshore grid is reported. The onshore voltage recovery to pre-fault value is slowest in case of AC cable system. Ekwue et al. [60] reports dynamic studies that demonstrate the compliance of FRT requirements of the National Grid Code in UK. The wind farm remains connected to the network for system faults lasting up to 140 ms. Due to ability of DFIG to control reactive power, the voltage recovery is shown to be fast. The study on grid code compliance in VSC based HVDC system in terms of FRT and reactive power capability is carried out in [61]. Due to fast switching capability of VSC, after fault clearance, $t > 0.25$ the active and reactive power is shown to recover smoothly the pre-fault condition. The reactive power capability of 400 MVA VSC is considered to be higher than an equivalent capacity of synchronous generator (compensator).

In the interconnection of oil and gas installation with OWF to the onshore grid, the AC fault occurrence will cause offshore AC voltage collapse and commutation failure in the offshore LCC [62]. During the fault, the commutation failure will lead to short circuit of DC link and DC voltage collapse. In this case, the power transmitted to onshore LCC gets reduced to zero. The crowbar of back-to-back converter acts to protect the generator and converter. However, the use of STATCOM aids to provide commutation voltage and support reactive power. It is also important to ensure offshore AC network remains in normal conditions even, if fault occurs on onshore grid. The active power transmitted to onshore significantly reduces due to onshore AC voltage drop. There are some methods for onshore grid FRT capability development. This includes reduction of wind farm active power on fault detection and addition of a DC chopper at STATCOM DC link. The latter approach though advantageous as wind farm is not affected, but dissipation of energy is a big question.

The development of meshed DC network did not withdraw enough attention due to lack of reliable operation of DC circuit breaker, wherein current can only be interrupted or even commutated into another branch when it goes through zero. High voltage DC circuit breaker still needs to be developed to operate in a multiterminal DC network. This issue becomes more serious in VSC multiterminal, since they cannot block fault currents. As the penetration of wind farm into grid increases, the FRT capability becomes more critical issue. This has resulted into revision of compliance in grid codes, according to which the wind farm must remain connected to the network during severe faults at the point of connection.

Probabilistic analysis is explored to know the occurrence of cable faults. Failure of a cable is at significant risk, the redundancy factor has to be taken into consideration. There are different protocols in IEEE offshore regulation concerned with safety, reliability, controller design, sensor, turbine battery bank and special transformer design [63].

3.4. Grid code compliance

In recent years, the power companies in countries like, Denmark, Germany and Spain have issued new grid codes addressed both at transmission and distribution for interconnection of wind farm with utility grid. The increased penetration of wind farm into grid has lead to several challenges in its operation and thereby enforcement of stricter grid codes [64,65]. This in turn resulted into significant impact on the development of WT generator technologies [66]. As a consequence, cost of individual turbine-generator set and communication system for control and protection has increased. Due to adoption of different grid codes by many countries, the manufacturers however, could not focus on cost-efficiency optimization, design and produce standard products in the power market. They need to meet the requirements of all grid codes without major modifications in the control algorithms and in the hardware.

Though the grid codes of different transmission system operators may differ [65], but should atleast include the following capabilities/characteristics:

- FRT capability,
- Reactive power capability,
- Power modulation capability,
- Frequency response capability and
- Various power quality related characteristics.

The new grid codes require limits on voltage total harmonic distortion (THD) level at PCC, FRT capability, in addition to participation of wind farms in regulation of frequency and voltage control. The fixed speed WT cannot control reactive power consumption and thus cannot meet new grid code requirements. While its use with VSC based DC transmission will eliminate some of the limitations and thus can satisfy the grid code requirements. Similarly, variable speed WTs has features to meet the requirements issued by utility companies. Variable speed operation with DFIG though has merits in terms of reduced converter rating but is sensitive to grid faults, needs special protection schemes and incapable to provide grid support during faults. On the other hand, WTs with full scale converter has all advantages of DFIG and capable to remain connected to grid during faults.

The THD levels in current signal for DG resources are well specified in [67]. Similarly, grid codes for voltage THD level as well as the compatibility levels for harmonics up to 40th order are defined in [68–70]. The design and control of grid side converter becomes important to meet the requirements of grid codes on these issues. Iov et al. [114] have analyzed compatibility levels of both voltage and current at PCC for different control strategies; voltage oriented control and adaptive band hysteresis current control at different grid conditions based on existing recommendations within grid codes. The authors have reported that voltage THD level remains below the recommendations, while the current THD in general depends on the grid impedance angle and the connection up to PCC. The THD level though gets increased with

grid angle and with use of cable between the transformer and the PCC, but still remains below the recommended grid codes.

3.5. System optimization approach

To analyze the system behavior during failures, it is required to have extensive knowledge and understanding on practical system maintenance with repair strategy for a long time run. The aim of this section is to provide basic understanding of how to assess the system performance and identify the weak points in the system. With increased knowledge of weak points and risks on OWFs, the challenging conditions and safety factor has to be considered [71]. Informed investment decisions can be included during the design phase. This action can reduce further costs due to supply interruptions and also decrease the need for maintenance. The authors in [72] propose a method based on Monte Carlo simulations to analyze the performance of different combinations of electrical configurations versus maintenance and repair strategies. The method allows in obtaining a complete probabilistic analysis of the variables for planners and designers. The proposed simulation method consists of several stages; (i) failure time decision for each component, (ii) graph theory evaluation, (iii) estimation of repair times, and finally (iv) estimation of maximum energy.

The procedure suitable for working with complex systems like a wind power system is described in [73]. The authors have analyzed different control strategies, and DC–DC converter is computed as best choice through real-time simulations. The study includes a table analysis which summarizes all control strategies by different converters. The investigation on degree of freedom, possible control action, technological choice, advantages and disadvantages for each converter, leads to an overview of different control possibilities that can be adopted for wind farm applications. It is reported that full bridge technology for DC–DC converter is suitable as it gives simple control modes and less expensive technology in comparison to double active bridge DC–DC converter.

The wind farm has an inborn stochastic characteristic and it is difficult to guarantee continuous supply but the probability or duration of interruptions can be reduced during its planning stage. One of the unique optimization techniques to calculate cost of energy in deregulated power networks avoiding instable permission and payment schedules that gives higher impacts on cost is discussed in [74].

3.6. Offshore wind speed forecast

The method to improve reliability of power prediction of a wind farm is suggested in [75]. In the approach, an extra safety margin is introduced with the availability of reduced power forecast curve to the transmission system operators for a time period of 24 h starting at midnight till the following day. If actual wind speed is higher than predicted, power output is limited to reduced power forecast curve. Wind farm with such a safety margin is capable to compete with the conventional power plants.

In [76], the authors present use of support vector machine as regression tool to forecast offshore wind speed. The wind prediction is carried out for hourly, daily and monthly data sets for Mumbai location obtained from Indian National Centre for Ocean Information Services. The details of wind forecast and power is calculated by removing a safety margin [77] and the gain achieved is compared with the conventional power plant.

The study in [78] shows that the development of wind energy in OWF is better in deep water regions to a range of 50–200 m from the sea coast. The European countries have the leading position and have been working on various projects of capacity up to20 GW. North America and Asian countries are in range of Megawatt production. The work in [79] aims to develop a cost effective method for determining the mechanical loads on different turbines by using Flight leader concept or by processing the data of wind turbines through SCADA and developing a software model to predict the total combined load of all the WTs. The SCADA system is also used to integrate avian radar technology with wind farm. This radar system functions as a continuous monitoring and control system and is capable to activate mitigation measures during conditions associated with bird mortality risk [80].

3.7. Condition/structural health monitoring

In general to mention here, the condition monitoring (CM) information in any utilities is utilized to detect incipient faults, and thus enable to perform more effective and efficient maintenance scheduling. From the operational point of view, any prospective maintenance policy based on CM information should have clear economic benefits; otherwise the initial outlay for the CM system and associated costs are not justified.

A significant amount of economic profit exists in operation of OWF. However, this depends on turbine-generator availability. The structural health monitoring (SHM) including turbine generator sets and associated auxiliary devices has proven as one of the most efficient methods to improve the availability of turbine-generator set. Both the size and the locations of WTs has led to new maintenance challenges as they are unique compared to traditional power generation sources. This is due to the fact that, physically reaching to each turbine location either weekly or monthly is not feasible. Moreover, a high maintenance cost is estimated with involvement of helicopters or crane for lifting spare parts up to the nacelle due to high probability of faults in gear-box, shaft and generator.

Some common assumptions made in respect of cost effective CM system applied to OWFs includes (i) increased lost energy, and thus revenue loss, due to larger size of offshore WTs and stronger wind profiles; (ii) longer downtimes; and (iii) larger and more costly components requiring higher outlay for operation and maintenance. However, large OWFs have their own distinct characteristics which further challenge these assumptions in respect of CM of offshore WTs.

The authors in [81] have developed a set of models to quantify the economic benefit of CM systems for offshore WTs of rating up to 5 MW. The cost effectiveness of CM system is demonstrated considering that accurate diagnosis in range of 60–80% cases are provided. Changes in maintenance practice, CM equipment, cost functions for model development, detailed modeling of equipment life stages and optimization of maintenance schedule with uncertainties need to be addressed.

An implementation of autonomous online monitoring systems with integrated fault detection algorithms can allow early warnings of mechanical and electrical faults to prevent major component failures. The SHM is one of many potential applications of wireless sensor networks (WSNs). However, in past, some system requirements in respect of SHM have been overlooked in the design and none of the protocols meet all of them. This could be dealt either by modifying the existing protocol or designing a new application oriented protocol [82]. A major proportion of energy consumption by the sensor nodes is due to data transmission. An energy efficient design is thus a prime concern. The WSNs normally use a cross-layered approach for protocol design. This ensures information gathered at a particular layer to be available to all the other layers. Thus a cross-layered approach results into maximization of information usage.

The EU Science and Technology key project FP7 “Health monitoring of offshore wind farms (HEMOW)” [83] aims to

analyze wind power generation systems and develop intelligent WSN and SHM technologies for the wind turbine blade, gearbox, generator, power electronics, and other structural components. In this project, a complete health analysis of wind power system, life cycle assessment, fault diagnosis, maintenance management programs, planning and scheduling system, including its design, production, installation, maintenance, and supply chain feedback are proposed to be carried out.

4. Other related factors

4.1. Planning and policy

The study on system impact is a basic step to define wind penetration in power system. The impacts of large-scale OWFs on system operation, voltage profile, power flow, short-circuit, transient stability, and system security need to be investigated and study is to be made during system planning. This in turn depends on grid strength at the connection point, i.e. location of wind farms, wind generator type, and correlation between wind power production and load consumption. Taiwan is energy dependent country and has promoted offshore wind power developments due to onshore site limitations. The authors in [84] have presented an operation and security study on Jhang-Bin OWF. The study conducted by authors suggests that connection of 108 MW wind farm to the 161-kV network in central Taiwan does not have any need for network reinforcement.

There is though always a balance between the reliability assessment and investment cost. The main reason for building OWFs is the availability of space together with good wind resources. Moreover, it has low noise and visual impact, which in turn affects the feasibility of onshore wind farms. And as a result, wind power industry has grown rapidly with remarkably increased number of offshore wind power plants being installed at a larger distance from the shore. All these aspects added together have made the interest on wind energy more topical than ever worldwide. Based on this, analysis on current policies related to OWF, and their implementation and corresponding dealing with the manufacturers are presented in [85]. An assessment is conducted by China Meteorological Administration's Wind Energy and Solar Energy Resources Evaluation Centre, which targets to increase the country's offshore wind potential up to 220 GW. The government of China has introduced offshore regulations, confirming who will develop wind farms and pay the price for the power generated [86]. Under these plans, Shanghai, Fujian, Zheijiang, Shangdong and Jiangsu are likely to have a combined offshore cumulative installed capacity of 10.1 GW by the year 2015 and 30 GW by the year 2020.

In [87], an analysis is presented for the long term measured onshore wind speed (1976–2000) at Doha International Airport. Similarly, another analysis is presented for the measured offshore wind speed at the Qatari Haloul Island. For onshore measurements, the average annual wind speed (at 20 m height) is found to be about 5.1 m/s. While in offshore, the average annual wind speed is found to be about 6.0 m/s, which is expected to be both technically feasible and economically viable.

The author in [89] presents review on DC medium voltage grid collection, which is connected to HVDC transmission system for higher power rating. In this case, medium voltage DC grid receives power from collection of WT output. The problems for control and protection are discussed for conversion of medium level to high voltage grid collection. Subsequently, the study [88] discusses power transmission through DC grid instead of AC grid using DC cables. This further shows reduction of cable size and visual of impact of converter stations.

In project [90] Efficient Development of Offshore Wind Farms (ENDOW), the main objective is to develop design tool that computes the power production from OWFs. Two types of model design tool are used. The first one is the atmospheric model, which calculates free flow in offshore conditions taking into account the terrain and meteorological effects, but wind turbines and resulting wake effects are not included. And second model is the wake model, which calculates the disturbance from WT on initial flow, excluding terrain and meteorological effects. The coupling of atmospheric and wake model is carried out with previous records and the tool is designed and tested to determine the compatibility of different models. The detail reports about component faults and power interruptions are neither required nor made available upon request. This problem can be worked out by keeping a transparency in database and protection of information [91]. It can be achieved by implementing reliability, availability, maintainability and safety (RAMS) engineering, starting from design to operational phases. Today's best-known wind turbine databases include scientific measurement and evaluation programme (WMEP), and the Wind Stats newsletter published in Denmark. Additional databases originate from Finland and Elforsk, Sweden. Besides these, data sources for WTs, a dedicated RAMS database is available under the heading of “Offshore Reliability Data” (OREDA), dedicated for data collection in the offshore oil and gas industry.

4.2. Economics and ecological

The prime factor in OWF development also includes its economic benefit. A feasible economic for the project is determined by electricity cost per unit (kilowatt hour), operational and maintenance cost, and capital cost [1]. The cost of electricity in wind farm is influenced by economic depreciation, operation and maintenance cost, tax paid to local and federal authorities, energy storage components, etc. The cost analysis also depends on the intermittency factor due to variation in wind speed. Further land rate, royalties and profit of the wind energy path, incentives, subsidies, production tax credits in the content of installation of wind energy are also to be taken into account for evaluation of wind farm economics. In present scenario, the capital cost of wind energy has progressively decreased, leading to gain in momentum for its utilization on offshore regions.

With the involvement of manufacturers and utility companies, a detailed analysis, both quantitatively and qualitatively of the vital drivers in development of OWFs must be assessed. A quantification basis for investment interconnection of different regions is to be made. The offshore networks promise greater flexibility and for large wind farms, greater cost effectiveness of transmission than simple point-to-point connections, either between AC systems or from single wind farm to shore need to be assessed. The complexity of overall control system increases with the number of terminals involved in DC grid. A study of the characteristics of the coordinated control command is essential to assess the economical and technical advantages and drawbacks of HVDC grids compared to radial connections [92]. For electricity generation from offshore wind energy, grid connection costs are the major component. An analysis is to be made for different connection costs on overall cost effectiveness from the consumers point of view.

For the response of these costs, following practices exist:

(i) *Super shallow system*: Grid operators provide substation and offshore connection includes onshore integration. Additional costs are recovered by conventional transmission charges which are paid by suppliers and passed on to electricity consumers.

(ii) *Shallow system*: Grid operators pay the cost for necessary grid reinforcement, and project developers pay the operational cost of transmission infrastructure.

Transfer costs savings are realized from super shallow approach instead of shallow approach. Capital costs are higher for offshore wind power producers who have more financial burden than grid operators. It is reported [93] that super shallow approach has the potential to reduce the producer's surplus amount, generated by wind farms which have low connection costs. When installation is included, then enhanced technology is considered. This is because, monopiles and gravity based structures in OWFs are costly in terms of fabrication and installation and as depth increases, the costs of such supported structures also increases as compared to floating supported structures.

EU's intelligent energy Europe (IEE) programme develops scientific view on offshore grid with a suitable regulatory frame in Europe which takes into account all technical, economical, policy and regulatory aspects into consideration. The innovative connection and interconnection concepts are important for making the offshore grid more cost-effective and efficient. An interconnected grid is developed in a step wise approach, adding direct interconnectors, hub to hub and tee in connection, step by step. It follows an iterative process combining the infrastructure cost model, power market and power flow model. Integrated solution like tee in and hub to hub solution is more beneficial in comparison to the conventional solution because these grid designs can increase system security and reduce environmental impact [94].

Grid connection costs are the major cost component in utilization of offshore wind energy for electricity generation. In [93], the effect of different attribution mechanisms of these costs on overall cost-effectiveness from consumers' perspective is analyzed. Another prime factor to be taken into consideration for development is the ecological aspects of OWFs. Due to the remarkable installation of OWFs in European countries, concerns get raised towards habitat of bird's life.

Installation of OWF makes a threat to the life of birds, due to higher probability of collision, affects the sea shore habitat loss, causes barrier in the migration route, and complete disconnection of ecological environment such as roosting and feeding sites. The probability of mortality rate for the birds has increased in the offshore regions [95]. The annual collision rate per turbine is estimated as 0.02–0.15.The environmental impact due to noise on sea living species is to be taken into account. The marine mammals, fishes are much sensitive to noise and can be affected to a remarkable extent due to construction of wind farm [96].

The study in [97] indicates no short-term (2 years) effects on the benthos in the sandy area between the generators, but has led to the establishment of new species and new fauna communities near the new hard substratum of the monopoles. The Offshore Windfarm Egmondaan Zee (OWEZ) has developed into a new type of habitat with a higher biodiversity of benthic organisms, increased use by the benthos, fish, marine mammals and some bird species and decreased use by several other bird species.

5. Recent trends

It is important to take into account the reliability, size, weight and efficiency of converter for OWFs applications. In order to reduce the losses, the topology that consists of reduced matrix converter (RMC), a high frequency transformer and a full bridge is proposed in [98,99]. A RMC has three phase input and single phase output, thus reduces the number of semiconductor devices. The authors in [100] demonstrate a higher efficiency for RMC compared to conventional converters. The topologies and control of RMC as VSC is presented in [101], whereas in [102], a modified and optimized space vector modulation is proposed for voltage source operation. Next, the authors in [103] present operation of RMC as current source converter by use of carrier based modulation and space vector modulation techniques. The operation of converter as current source is advantageous since in series connection of WT, the current variable, unlike voltage is kept constant. Space vector modulation is shown to be more efficient and produces low frequency harmonics than carrier based modulation in operation of RMC.

The harmonic resonance is a major issue in AC transmission than DC transmission. The AC submarine cables produces a potentially magnified low order harmonics and high shunt capacitance, which causes capacitive charging and discharging current and generate reactive power. The spectral analysis by state equation method for modeling submarine cables in π equivalent circuit and using passive filter to mitigate harmonics is discussed in [104].

For optimizing reactive power in OWF, an adaptive particle swarm optimization (PSO) technique is used in [105] to solve reactive power dispatch problem. The PSO algorithm can be applied to linear and nonlinear system and free from parameter tuning and from the burden of selecting the most appropriate swarm (population) size. The optimization task for management of reactive power can be divided into two stages; before installation and continuously during operation. Proper reactive power management can give a better economy results. HVDC power transmission and distribution can provide economic advantages and higher efficiency in comparison to the HVAC transmission and distribution system. The advantage of HVDC is the ability to transmit large amount of power over long distance. It is used for the connectivity of remotely located grid, as AC cable becomes impractical beyond the length of 50–100 km due to the concern of capacitance per unit length of transmission line. So for integration of large OWFs, use of HVDC cables compared to extra high voltage AC cables for transmission are feasible option. In [106], the comparison between HVDC and HVAC; HVDC transmission and medium voltage DC distribution system for offshore wind energy with practical issues like medium voltage DC–DC converter, medium voltage cables and DC protection, multiterminal HVDC offshore grid are discussed. The medium voltage DC collection and distribution system includes various component; AC–DC converters, a line frequency converter or power transformer, phase reactor, AC and DC filter, etc. With use of medium voltage DC cable, DC protection and site test results, the optimal goals of DC transmission is achieved.

When HVDC is concerned, then the need of converters is mandatory. LCC and VSC converters are widely used in HVDC systems but now-a-days a new configuration, bridge of bridge converter (BOBC) is suggested [107]. The BOBC has six arms with sub-modules which are stand alone converters connected in series to realize high voltage operation and additional resistive–capacitive component need not to be connected in parallel for voltage matching. The BOBC may also use discrete voltage steps to achieve sine waveforms, which gives low harmonic content and switching losses. It also allows the elimination of extra high voltage transformer. The authors analyze BOBC converter topology in comparison to VSC for offshore wind energy conversion application. The efficiency of the HVDC–BOBC is reported to be 87%.

The construction/installation of OWF faces many constraints like, erection and transportation, the development of an intelligent control system is proposed with jack-up offshore platform. The jack-up platform includes larger area and shallower draft by which the difficulties that come during the construction of OWF are removed. Jack-up platform in offshore requires a remote, high precision intelligent control system by using status information of sensors, a database system and a pier side control interface. The paper [108] describes the development of jack-up offshore wind platform by implementing a remote controlled master control

system. The goal of constructing the world's largest offshore wind farm project (500 MW) site is located approximately 25 km offshore within the Thames Estuary Strategic Environmental Assessment Area and adjacent to two sand banks known as the Inner Gabbard and The Galloper. This project will feature 140WTs, each having a rated capacity of 3.6 MW. A comparative study for the selection of the adequate cathodic protection system and the installed design with the use of advanced computer modeling technologies is presented in [109].

In comparison to onshore wind farm, OWF faces more complicated environmental condition due to stochastic nature of wind. The OWF can be analyzed by using a floating supported structure and using simulation tools capable of predicting the coupled wind-inflow, aerodynamic (aero), control system (servo), and structural-dynamic (elastic), incident waves, sea current, hydrodynamics (hydro), and foundation dynamics of the support structure, including the platform, blades, tower and drive train in a coupled simulation environment by an open source code [110]. The fuzzy analytical hierarchal process is applied to obtain the important sequence and determine the key success factors of offshore wind energy in Taiwan. This analytical hierarchal process (AHP) is used for multi-criteria decision making and practical decision making problems [111]. Fuzzy AHP follows certain steps such as hierarchally structuring, development of judgment matrices by pair-wise comparison, assessment of global priorities, and calculation of global priorities. The study in [112] reports a practical approach in which fuzzy analytical hierarchal process is applied to five different sites in Taiwan and best results are obtained for Changhua coastal area for the development of first OWF.

In another paper [113], the authors suggest an innovative sea water desalination system for a large scale OWF. A direct coupling between offshore wind powers with high energy consuming seawater desalination system is proposed. The system uses 100% offshore wind power and adopt variable condition for optimal control to maintain energy consumption per unit, when fresh water production changes due to wind power fluctuation.

6. Conclusion

In past few years, a significant interest has drawn among the developers to harness freely available energy from OWF. This paper has reviewed extensively the development of OWF, including technology, planning, and ecological aspects. The development of engineering modeling and analysis tools will help to reduce overall offshore facility costs and to design the next generation innovative large-scale turbines optimized for installation and operation in the marine environment. The offshore wind turbines face greater potential for corrosion from exposure to seawater and hence should be designed more robustly with less maintenance requirement. The study on dynamic behavior of each wind turbine, rather than equivalent wind farm model should be assessed. An improved coordinated control design for individual wind turbines may minimize the wake effects. The development of enhanced controller will facilitate wind farm dynamic performance compatible with conventional synchronous plant (i.e. to provide support to power system operation in terms of dynamic voltage and frequency control).

Installation and maintenance of wind farms at sea is much more complex than on the land, thus requiring special equipments and good weather conditions. Higher winds may lead to storms, and big waves, and sea water being salty causes corrosion to the structures. Cost improvements could also be envisaged through enhanced research and development efforts focusing on specific components, or on new materials.

OWF of gigawatt (GW) capacity will require the use of floating turbines, which are still in the development stage. This may drive a high cost for such projects. The physics of conventional wind turbines results into an unstable machine when used with floating type structures. However, with significant research, the road map of such turbines is expected to be brighter.

Acknowledgements

The first author acknowledges the receipt of Maulana Azad National Fellowship (MANF) scheme under University Grants Commission (UGC), New Delhi, India.

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